Quarkonium suppression as a probe of a saturated gluon plasma?

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Abstract:

A dense parton system is expected to be formed in the early stage of relativistic heavy-ion collisions at RHIC energies and above. The probability of a quark gluon plasma production and the resulting strength of its signatures depends strongly on the initial conditions associated to the distributions of partons in the nuclear wave functions. At very high energies, the growth of parton distributions should saturate, possibly forming a Color Glass Condensate, which is characterized by a bulk momentum scale Q_s. As a direct consequence, the possible signatures of the QGP should be Q_s-dependent if the saturation scenario is valid for RHIC and LHC. In this Letter we assume the saturation scenario for the QGP formation and estimate the saturation scale dependence of quarkonium suppression. We conclude that, if this scenario is valid, the Υ suppression only occurs at large values of Q_s.

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High energy heavy-ion collisions offer the opportunity to study the properties of the predicted QCD phase transition to a locally deconfined quark-gluon plasma (QGP) [1]. A dense parton system is expected to be formed in the early stage of relativistic heavy-ion collisions at RHIC (Relativistic Heavy Ion Collider) energies and above, due to onset of hard and semihard parton scatterings. These processes happen in a very short time scale after which a dense parton gas will be formed, not immediately in thermal and chemical equilibrium. Secondary interactions among the produced partons may lead to thermalization if the interactions are sufficiently strong, allowing to study the subsequent dynamical evolution of the system using hydrodynamic-based models [2]. Exactly how this parton gas equilibrates and a thermalized plasma of quarks and gluons is formed requires solving a kinetic equation, given appropriate initial conditions and a detailed knowledge of the microscopic processes by which the quanta exchange energy and momentum. This topic is currently under intense debate [3, 4, 5].

The search for experimental evidence of this transition during the very early stage of the AA reactions requires to extract unambiguous characteristic signals that survive the complex evolution through the later stages of the collision. One of the proposed signatures of the QCD phase transition is the suppression of quarkonium production, particularly of the J/ψ [6]. The idea of suppression of $c\bar{c}$ mesons J/ψ, ψ', etc., is based on the notion that $c\bar{c}$ are produced mainly via primary hard collisions of energetic gluons during the preequilibrium stage up to shortly after the plasma formation (before the initial temperature drops below the production threshold), and the mesons formed from these pairs may subsequently experience deconfinement when traversing the region of the plasma. In a QGP, the suppression occurs due to the shielding of the $c\bar{c}$ binding potential by color screening, leading to the breakup of the resonance. The $c\bar{c}$ ($J/\psi, \psi', ...$) and $b\bar{b}$ ($\Upsilon, \Upsilon', ...$) resonances have smaller radii than light-quark hadrons and therefore higher temperatures are needed to dissociate these quarkonium states.

The probability of a thermalized QGP production and the resulting strength of its signatures strongly depends on the initial conditions associated to the distributions of partons in the nuclear wave functions. At very high energies, the growth of parton distributions should saturate, possibly forming a Color Glass Condensate [7] [For a pedagogical presentation see Ref. [8]], which is characterized by a bulk momentum scale Q_s. This regime is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wave function (parton saturation) and very high values

1

of the QCD field strength squared $F_{\mu\nu}^2 \propto 1/\alpha_s$ [9]. In this case, the number of gluons per unit phase space volume practically saturates and at large densities grows only very slowly (logarithmically) as a function of the energy [10]. If the saturation scale is larger than the QCD scale Λ_{QCD}, then this system can be studied using weak coupling methods. The magnitude of Q_s is associated to the behavior of the gluon distribution at high energies, and some estimates has been obtained. In general, the predictions are $Q_s \sim 1$ GeV at RHIC and $Q_s \sim 2 - 3$ GeV at LHC [11, 12].

Recently, Mueller has proposed idealized initial conditions for a saturated nuclear wave function and shown that the evolution of single particle distributions could be described by a nonlinear Landau equation [13]. This equation was numerically solved in Ref. [3] and in a "self-consistent" relaxation time approximation in Ref. [5]. One of the main conclusions of these studies is that the equilibration time and the initial temperature of the plasma have a strong functional dependence on the initial gluon saturation scale Q_s. As a direct consequence, the possible signatures of this saturated gluon plasma should be Q_s-dependent if the saturation scenario is valid for RHIC and LHC. We denote saturated gluon plasma, the plasma formed from the collision of two nuclei with saturated nuclear wave functions. Our goal in this Letter is assuming the saturation scenario for the QGP formation, estimate the quarkonium suppression and its dependence in the saturation scale at LHC energies.

Lets start from a brief review of the quarkonium suppression in heavy-ion collisions. The heavy quark pair leading to the quarkonia are produced in such collisions on a very short time-scale $\sim 1/2m_Q$, where m_Q is the mass of the heavy quark. The pair develops into the physical resonance over a formation time τ_f . For a confined surrounding, the bound states of $c\bar{c}$ and $b\bar{b}$ interacting via two forces: a linear confining potential and a color-Coulomb interaction. In the plasma phase, the linear potential is absent due to the high temperature leading to deconfinement and the color charge is Debye screened by a cloud of surrounding quark-antiquarks pairs which weaken the binding force between the $Q\overline{Q}$ pair, thus reducing the color charge seen by the other (anti)quark. Basically, above the critical temperature T_c, we have

$$V(r) = -\frac{\alpha}{r} + \sigma r \Rightarrow V(r) = -\frac{\alpha}{r} \exp(-\mu_D r)$$

where α and σ (the string tension) are phenomenological parameters and μ_D is the Debye mass. As discussed in Ref. [14], for values of the screening mass

above a certain critical value μ_i^{diss} $(i = J/\psi, \psi', \chi_c, \Upsilon, \Upsilon', \chi_b)$, the screening become strong enough for binding to be impossible and the resonance no longer forms in the plasma. As a result, the Q and $\overline{Q}$ drift away from each other, after leaving the interacting system to form a charm and bottom mesons, which subsequently decays into leptons to be detected. The critical screening mass for quarkonia are summarized in Table 1.

The discussion above implies a procedure to determine if quarkonium suppression is expected. Basically, if we known the evolution of the screening mass during the collision process we can estimate what quarkonia will be effectively suppressed. At screening mass values greater than μ_i^{diss} for values of time above (or equal) to the formation time of the bound state (τ_F), the bound state does not be formed. Therefore, we can analyze the quarkonium suppression considering the dynamical evolution of the screening mass [15]. An expression currently found in the literature for the screening mass is the following:

$$\mu^2 = -\frac{3\alpha_s}{\pi^2} \lim_{|\overrightarrow{q}| \to 0} \int d^3k \frac{|\overrightarrow{k}|}{\overrightarrow{q}.\overrightarrow{k}} \overrightarrow{q}.\nabla_{\overrightarrow{k}} f(\overrightarrow{k}) \,, \tag{1}$$

where α_s is the strong coupling constant and $f(\overrightarrow{k})$ is the phase space density of gluons. This expression was derived in Ref. [16], following the standard calculation (in the Coulomb gauge) of screening in the time-like gluon propagator in a medium of gluon excitations. In the case of an ideal equilibrium gluon gas, $f(\overrightarrow{k})$ is the Bose-Einstein distribution and the above expression implies the well-known screening mass $\mu^2 = 4\pi\alpha_s T^2$. Although the extrapolation from this expression for a system of highly non-equilibrated gluons produced in the early stage of heavy ion collisions be useful in the literature, is but may not be well defined.

An alternative expression for the screening mass has been derived in Ref. [13] considering the saturation scenario for the QGP. This scenario is based on the observation that at very high energies the parton densities in large nuclei reach saturation and the number of partons becomes very large, allowing a description by a classical effective field theory (EFT) [17]. In this approach (the McLerran-Venugopalan approach), the valence quarks in the nuclei are treated as classical sources of the color charges, with the gluon distribution for very high nuclei obtained by solving the classical Yang-Mills equation. The behavior of the gluon distribution is characterized by the saturation momentum Q_s, below which the distribution reach their maximum

3

value, i.e., the distribution exhibits saturation. When quantum corrections are included, a Wilsonian renormalization group picture emerges [18]. The structure of classical fields remains intact, the scale Q_s grows because hard gluons (harder than the x scale of interest) in the source increases the typical size of color fluctuations. Due to the large occupation number, the small x partons described by the EFT constitute a color glass condensate [7]. Since the classical fields of the two nuclei are known, they provide the initial conditions for the gluon fields produced in the nuclear collision, with the particle production after the collision described by the space-time evolution of classical gauge fields. The problem of finding the evolution of the classical gauge fields in nucleus-nucleus collisions has been addressed in lattice simulations [19], allowing to compute the energy and the number of produced gluons at central rapidities [20]. On the other hand, in Ref. [13] Mueller has investigated the approach to equilibrium in the McLerran-Venugopalan approach, considering only elastic scattering and derived a Landau-type equation for the single particle distributions $f(x, p)$. The idealized initial condition for this transport equation is assumed as given by

$$f(x, p) = \frac{c}{\alpha_s N_c} \frac{1}{t} \delta(p_z) \theta(Q_s^2 - p_t^2) \ , \tag{2}$$

where $c \approx 1.3$ is the parton liberation coefficient accounting for the transformation of virtual partons in the initial state to the on-shell partons in the final state. In Ref. [3], the transport equation has since been solved numerically using the above initial condition and the approach to equilibrium studied quantitatively, verifying that the equilibration time and the initial temperature of the saturated gluon plasma have a strong functional dependence on the initial gluon saturation scale Q_s. Furthermore, Mueller has assumed that at early times, in the maximum distance $1/q_{min}$ corresponding to the minimal momentum transfer q_{min} one has at most one scattering. This condition regularize the logarithmic collinear divergence in the transport integral and provides an alternative expression for the dynamical screening in the system of gluons produced at central rapidities, which are completely out of equilibrium. One obtains [13]

$$\mu^2 = \left(\frac{c \alpha_s N_c}{\pi}\right)^{\frac{2}{3}} \frac{Q_s^3}{(Q_s t)^{2/3}} \ . \tag{3}$$

As shown in Ref. [3], this expression for the dynamical screening mass is larger than the equilibrium expression Eq. (1) for early times and is almost

4

identical at late times [The difference between the two expressions is ≈ 0.05 GeV for $t \approx 0.04 fm$ and is approximately zero for $t = 1fm$]. As the heavy quark production and the formation of bound states are predicted to occur in the initial stage of the deconfined phase, we will use the expression (3) for the dynamical screening mass in our analyzes, which implies an upper limit for the predictions of quarkonium suppression.

Now let us consider a central collision in a nucleus-nucleus collision, which results in the formation of a quark-gluon plasma. Consider the central slice ($y = 0$) of a collision which leads to the production of a heavy quark pair from initial fusion and to a QGP. During the initial interaction period, heavy quarks will be produced through gluon fusion and quark-antiquark annihilation. Like gluon and light quark production, heavy quark production through the initial fusion is very sensitive to the parton distributions inside the nuclei. Although the cross sections for heavy quark production in RHIC and LHC are strongly modified by the presence of the high density effects [21, 22], the quarkonium production rate should be large enough for any suppression to be observable. The charm quarks will be produced on the order of a time scale $1/2m_c \approx 0.07 fm$, while the bottom quarks will similarly be produced over a time of $\approx 0.02 fm$. Thus immediately upon production, these quarks will find themselves in a deconfined matter which is highly out of equilibrium and rapidly evolving towards kinetic equilibration. In the plasma rest frame, the $Q\overline{Q}$ forms a bound state in the time $t_F = \gamma\tau_F$, where $\gamma = \sqrt{1 + (p_T/M)^2}$ (M is the onium mass) and the formation times, τ_F, are $\tau_F^{\Upsilon} = 0.76 fm$ and $\tau_F^{J/\Psi} = 0.89 fm$. Here we will concentrate in the small p_T region, where $t_F \approx \tau_F$. The color charge of the heavy quark will be subject to screening due to the presence of the saturated gluon plasma. If the dynamical screening mass μ [Eq. (3)] is larger than the critical screening mass μ_i^{diss} [Table 1], the Q and $\overline{Q}$ cannot form a bound state and the $Q\overline{Q}$ system will dissociate into a separate Q and $\overline{Q}$, which subsequently hadronize by combining with light quarks or antiquarks to emerge as "open flavors" mesons. We will concentrate our analyzes in the Υ suppression at LHC energies, since at current energies, the situation of J/ψ suppression is rather ambiguous because the bound state can also break up through interactions with nucleons and co-moving hadrons, i.e., QGP production has not been proved to be the unique explanation of the observed suppression even though an increased density of secondary production is needed. Because the Υ is much smaller than $c\overline{c}$, a much higher dynamical screening mass is necessary to dissociate the Υ,

5

providing a valuable tool to determine the initial state of the system and the characteristics of the plasma [23]. Moreover, we will consider the dynamical evolution of the screening mass for $t > t_0$, where t_0 is inferior limit for the application of the transport theory. For the LHC energies which we are interested $t_0 \leq 0.18 fm$ [3].

In Fig. 1 we present the time dependence of the dynamical screening mass as predicted in a saturated gluon plasma for some values of the initial gluon saturation scale. We can see that our predictions are very sensitive on the saturation scale. Considering that the coupling constant is constant and equal to 0.3, we have that for small values of the saturation scale ($Q_s \approx 1.0$ GeV) our results predict that the meson Υ is not dissociated, causing it to escape unscathed. For medium values of Q_s (≈ 2.0 GeV) the dynamical screening mass is larger than the dissociation mass only for the early stage of evolution, where the formation of a bound state is unexpected. A similar scenario is obtained if we consider the values of c (=1.23), α_s (=0.6) and Q_s (=1.41) derived in Ref. [24], where the recent data of the PHOBOS collaboration for the charged multiplicity distribution were analyzed considering the saturation scenario. Therefore, if the saturation scenario is valid at RHIC with the typical values for α_s and Q_s extract from the multiplicity distribution we does not expect the Υ suppression for the current energies in this collider ($\sqrt{s} = 130 GeV$). Only for large values of the saturation scale we predict the Υ suppression, since by the time that the upsilon is formed the dynamical screening mass is above of μ_{Υ}^{diss}, required to inhibit its formation.

In Fig. 2 we present the dependence of the dynamical screening mass in the the coupling constant for two typical values of the saturation scale. We analyze the behavior of the dynamical screening mass in the interval of times between the inferior limit for the application of the transport theory ($t \approx 0.2$ fm) and the characteristic value of formation time ($t \approx 0.8$ fm). We verify that if the plasma is characterized for a small value of Q_s , the suppression of the meson Υ is only expected for early times of evolution and large values of the coupling constant, where the perturbative calculations becomes questionable. For large values of the saturation scale, the Υ suppression is predicted for $\alpha_s \geq 0.3$ in the initial stage of the kinetic evolution. However, at late stages the Υ dissociation is not expected. For comparison, we also present in Fig. 2 the dissociation mass of the J/Ψ meson. We verify that in this case the complete suppression is expected to occur in the presence of a saturated gluon plasma.

In Fig. 3 we present the dependence of the dynamical screening mass

6

in the saturation scale for a typical value of the coupling constant. We verify that the dissociation of the Υ must occur only if the saturated gluon plasma is characterized by large values of the momentum saturation scale. In other words, the presence of Υ suppression indicates that if a saturation scenario is valid, the initial nuclear wave function are characterized for a bulk momentum scale $Q_s \geq 1.5$ GeV. Therefore, the Υ suppression may be an indirect probe of the nuclear wave functions, and consequently, from the Color Glass Condensate, allowing to constraint the initial gluon saturation scale.

Some comments are in order. In this Letter we have assumed that the saturation scale is in the range 1-3 GeV at the RHIC and LHC energies, and derive the respective pattern of Υ suppression. A more precise constraint of the saturation scale value can be obtained if we consider the eA processes, which could be analyzed in the future eA colliders at RHIC and HERA. In particular, the analyzes of the slope of the nuclear structure function [12] and the ratio between the transverse and longitudinal structure function [25] are potential observables to determinate the value of Q_s. Our results demonstrate that this independent constraint of the saturation scale is fundamental for the description of the observables in AA process.

Lets compare our results with other predictions of Υ suppression. In Ref. [15] the expression (1) has been used to analyze the evolution of the dynamical screening, as well as the onset of quarkonium suppression, considering initial conditions provided by the parton cascade model. One of the main conclusions of that analyzes is that the Υ suppression is only expected at LHC energies. Distinctly from our results, that predicts that the suppression must occur only for the quarkonia produced in the initial stages and at large values of the saturation scale, these authors predicts the complete suppression, since the screening mass is ever above of the dissociation mass in the dynamical evolution. Such result is associated to the initial conditions used as input in the calculations, which does not consider a saturation criterium in the nuclear wave functions. Similar situation occur if we compare our results with that obtained in Ref. [26], where the quarkonium suppression in an equilibrating quark-gluon plasma was evaluated considering two mechanisms: the Debye screening and the gluonic dissociation, concluding that the Debye screening is not effective for Υ suppression at the LHC energy. This result derives from the self screened parton cascade model, which leads to small Debye mass and implies that at the formation time of the Υ, the Debye mass drops below the value of μ_{Υ}^{diss}, required to inhibit its formation,

7

causing it to escape unscathed. Therefore, the main difference between the predictions for Υ suppression is associated to the use of distinct initial condition for the dynamical evolution. Consequently, independent searches of the gluon saturation of the nuclear wave function are required to discriminate between the distinct approaches.

In brief, we have seen that if the saturation scenario is valid for RHIC and LHC, with the nuclear wave functions characterized by a bulk momentum scale Q_s, the pattern of quarkonium suppression is also Q_s dependent. We have verified that the Υ suppression is only expected at large values of the saturation scale, allow us to constraint the values of this scale. In other words, the presence of Υ suppression is an indicative of the presence of a saturated gluon plasma, characterized by a large value of the initial gluon saturation scale in the nuclear wave functions. Of course, more quantitative analyzes can be made if this scale was derived in an independent process.

Acknowledgments

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Tables

State	J/ψ	ψ'	χ_c	Υ	Υ'	χ_b
μ_i^{diss} (GeV)	0.70	0.36	0.34	1.57	0.67	0.56

Table 1: The dissociation screening mass for quarkonia.

Figure Captions

Fig. 1: The time dependence of the screening mass in a saturated gluon plasma for some typical values of the saturation scale Q_s and the coupling constant α_s. The horizontal line characterize the dissociation screening mass for the meson Υ.

Fig. 2: The dependence of the screening mass in the coupling constant for two instants in the saturated plasma evolution. The long dashed and dotted-dashed curves characterize the dissociation screening mass for the mesons Υ and J/Ψ, respectively.

Fig. 3: The dependence of the screening mass in the saturation scale for two instants in the saturated plasma evolution. The long dashed curve characterize the dissociation screening mass for the meson Υ.
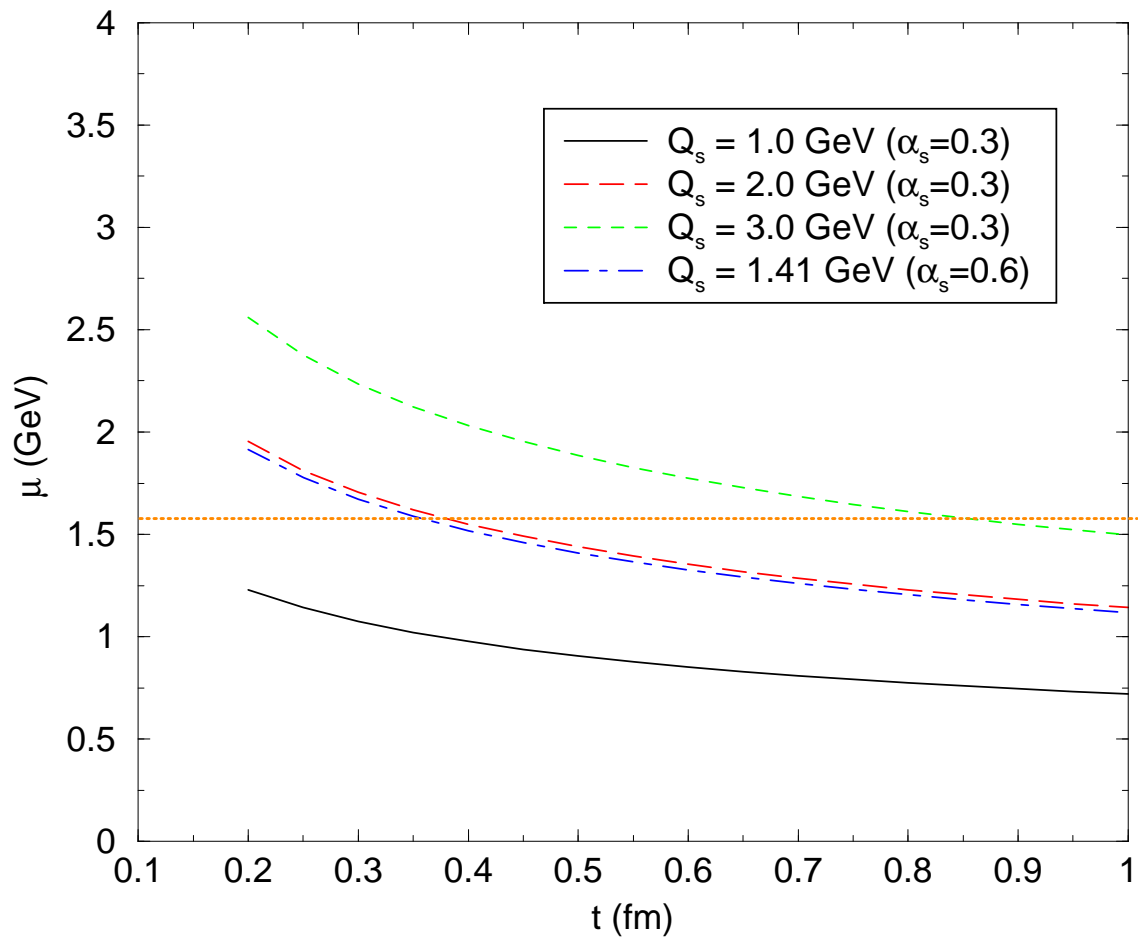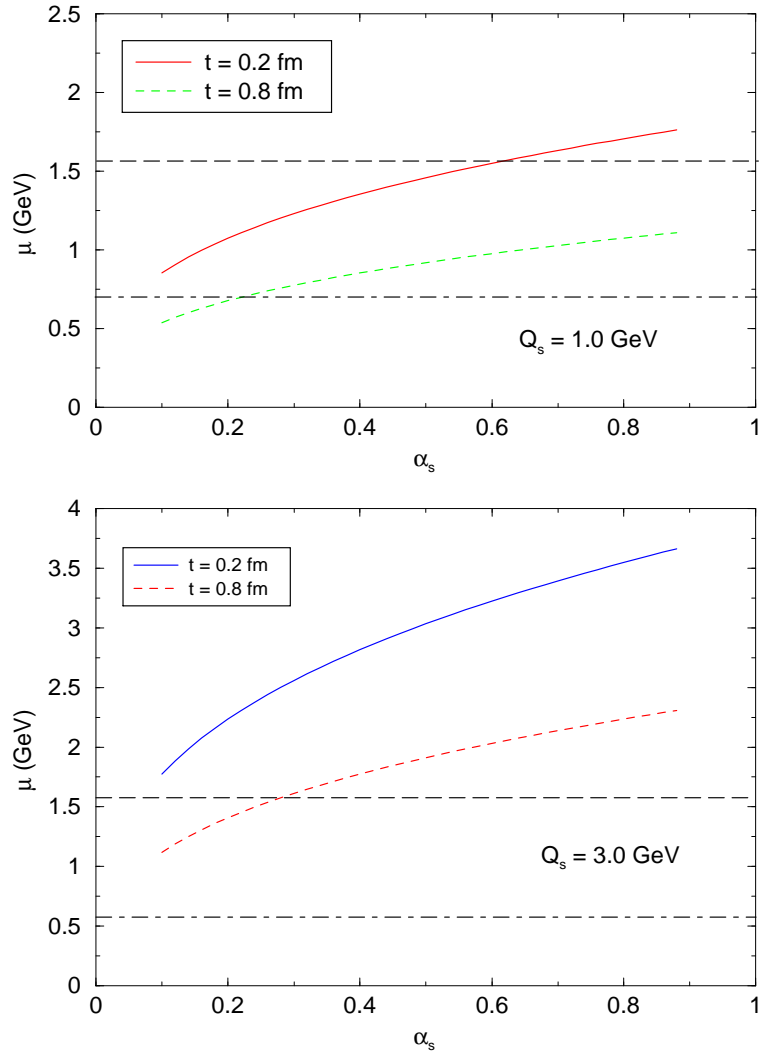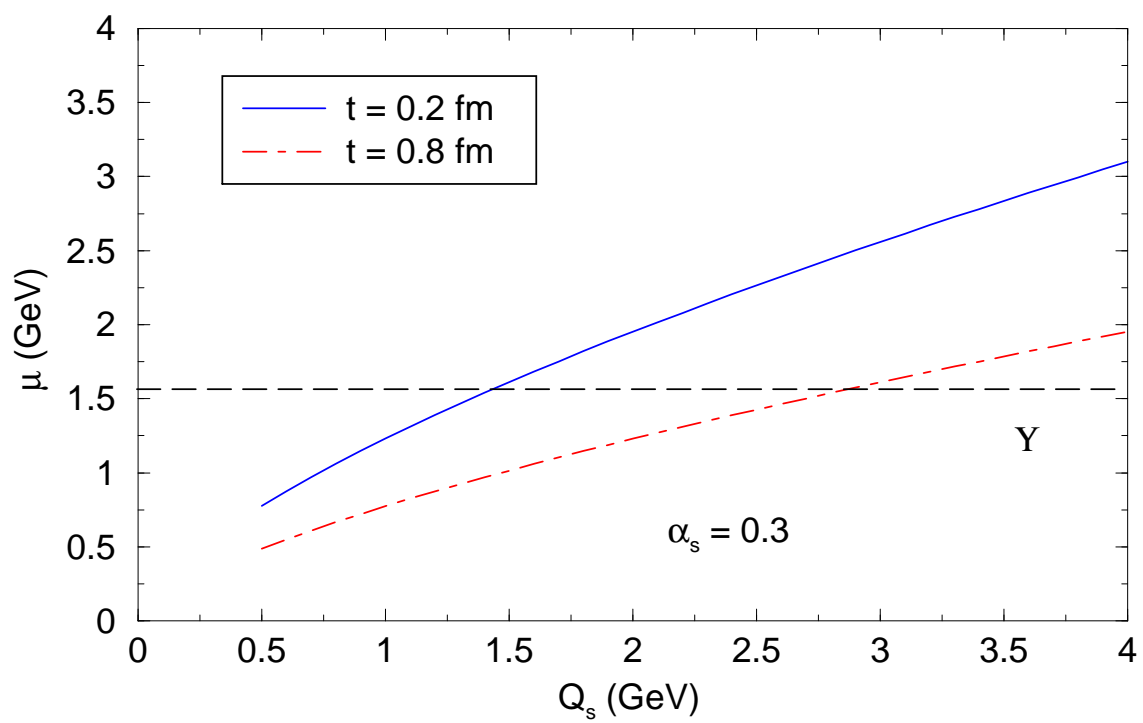
Figure 1:

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13

Figure 3: